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Design of Miniature Space Grade Navigation Camera for Lunar Mission

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Abstract—: **Vision based navigation and path planning for the Indian Lunar Rover calls for Stereo navigation cameras. These Navcams proposed to be mounted at the front face of the Rover, give information of obstacles like boulders/ craters/ pits on the path ahead. By analyzing the scene captured by these Navcams, the trajectory of the Rover will be planned and executed. The design of a miniature Navcam to operate reliably in space environment calls for high level of integration of many systems on a single chip thus minimizing power consumption, volume and weight onboard[1,2]. This paper describes the design aspects of the navigation camera which is developed at LEOS, ISRO.**

Keywords- Navigation, pixel, image, vision

I. INTRODUCTION

The proposed lunar mission consists of an Orbiter, Lander, and Rover. Once Lander-Rover reaches 100 km polar orbit around the Moon, the landing system will be commanded for its controlled descend trajectory towards the Moon's surface. Following the landing, the motorized Rover with arm and scientific instruments will be released on the lunar surface. The Rover will have the instruments meant for in situ analysis namely robotic arm, driller and science payloads. Orbiter can look at the Moon from 100 km orbit height. Lander can sit in one spot and investigate a landing site. The entire operation is an image intensive process. For successful operation of the rover and other instruments, it should be equipped with Navigation cameras. The development of a miniature digital space grade camera based on Active Pixel Sensor (APS) [2, 3] which is completed at LEOS is presented here.

II. REQUIREMENT OF NAVIGATION CAMERA

The mobility of the Rover is planned to be semi autonomous. A pair of Navigation cameras would provide the imagery of the terrain ahead. A ground based image analysis and path planning system would use these images to construct a Digital elevation model of the surface features imaged. Considering the slow speed of the Rover which is 1cm / sec and the data rate of the communication links between Rover- orbiter-ground stations (1 kbps), the mobility of the rover is restricted to 5 m for each path planning. The Navigation cameras are required to provide a clear image of the path ahead for at least 10 m range. They must have coverage of minimum 6 m across the track / path. Also the blind distance at the front of the rover which could not be imaged must be maintained the minimum**.** The size of the object to be detected by the Navcam is derived from the mission operation requirement. The stereo based DEM generation and photogrammetric depth measurement demands that the FOV of both Navcams must overlap on each other for more than 60%. Hence the Navcams are oriented on the Rover deck to meet the above requirements.

TABLE I. MISSION REQUIREMENT

Parameter	**Value**
Resolve objects	20 mm @ 10 meter
Image over lap	> 60%
Scene illumination	0.3 lux to 1,50,000 lux
Frame rate	3 fps
Irradiance levels	1370 W/m^2
Volume	< 175 cc (or) 50 x 50 x 70
Weight	< 200 gm
Power	<2 watts
Operating	- 55^0 C to + 80^0 C
Storage	- 150^0 C to + 80^0 C
Mechanical I/F	4 Holes M3 on Rover Plat form
Environmental	Thermovac 10^{-12} bar.
Electrical I/F	Serial digital
Rad hardness	Components to with stand 10

A. Configuration of Navigation Camera

The camera consists of STAR 1000 *Rad-hard* APS monochrome detector and Actel *Rad*- hard FPGA. The image is acquired and sent to Rover On-Board computer through serial digital interface. Images are obtained simultaneously from a pair of cameras. The azimuth / depth information is derived using appropriate stereo imaging software on ground from the pair of images obtained.

B. Mounting and orientation of Navigation cameras on the Rover.

The FOV requirement is met by suitable canting as derived below.

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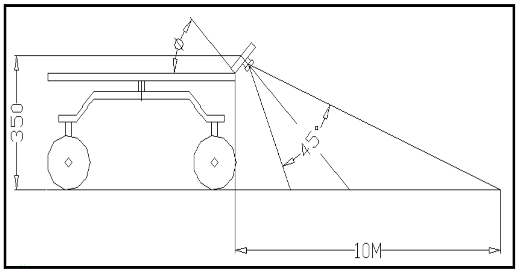


Figure 1. Canting

As per the mounting of cameras, the centre height from the Lunar soil would be 350mm. To make the top extreme ray to just cover the 10m distance the cant angle \`Ø' works out to be 25°. (Fig.1.) This is advantageous for the minimum blind distance of 302 mm. With 25° cant angle the top extreme row pixels cover the images up to 10 m range and the bottom row of pixel cover objects at a minimum blind distance of 302mm in front of the Rover. The mounting orientation about the Z direction of the Rover affects the image overlapping between the cameras.

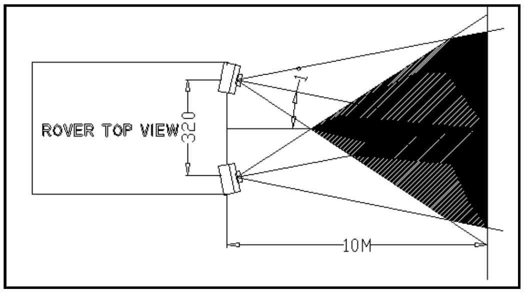


Figure 2 Image Overlap

The maximum distance covered is 10m and the baseline separation between cameras is 320mm. By tilting the camera by **1°** the centre pixel covers the center of path at 10m distance [Tan $^{-1}$ (160 / 10000)]. This cant angle enables maximum overlapping of images up to 10 m. (Fig.2.) The cant angle of both the camera will be synchronized.

*C. Specifications of Navigation Camera***.**

Detector : STAR 1000 APS
No of pixels : 1024×1024
Pixel dimension : 15 µm x 15 µm
Spectrum : Visible
Power : < 1.5 watt
Frame Rate : 3 fps
Data rate : 24 Mbps
Interface : Serial interface
Image size on sensor : 8.5 x 8.5 mm
Supply Voltage : 5V ± 150mv
FOV : 45° (H) x 45° (V)
Focal length : 14.5 mm.
Size of camera : 100 x 100 x 75 mm
Weight : 250 gm including optics
Operating Temperature : -35 to +80 ° C

D. Additional Features built into Camera by Design

a. Serial digital Interface.
b. Provision for both tele-command and telemetry.
c. Auto Exposure control.
d. Commanded exposure control

III. DESIGN OF NAVIGATION CAMERA.

The major functional components of the camera are

- Optics,
- Mechanical design
- Electronics (FPGA) and the Detector.

A. Optics design / specifications

TABLE II. LENS SPECIFICATIONS

Lens parameter	Value
Focal Length	25mm
Maximum Relative Aperture	1:1.4
Iris	F1.4~Close
Mount	C-mount
Minimum Object Distance	0.5m (from front vertex)
Angular Field of View	28.7^0 x 21.7^0
Optical Back Focal Distance	14.32mm (in air)
Operation	Iris, Focus : Manual
Operation Temp	-10~+50^0 C
Filter Size	30.5mm P0.5
Weight	Approx. 90g (3.2oz)

B. Mechanical Design of NAV SENSOR.

To optimize the mass, the camera housing fabrication using new polymer material PEEK (Poly Ether Ether Ketone) is envisaged. This glass fiber reinforced polymer has better temperature characteristics than aluminium alloy AL 6061, and can withstand the high energy particle radiation with a loss of only 10% of its strength.

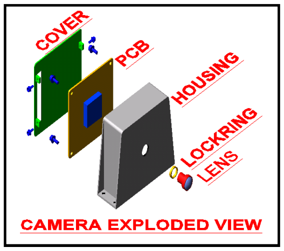


Figure 3 Mechanical parts

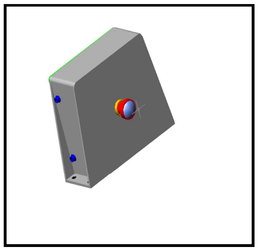


Figure4. 3D view of Nav Cam

C. *Electronic design of NAV camera.*

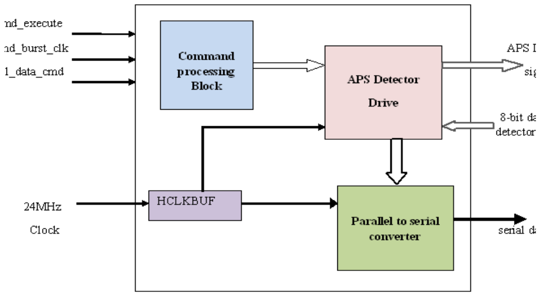


Figure 5. Block diagram of camera electronics

1) Choice of Detector:

The camera uses a CMOS active pixel image sensor (Cypress STAR 1000 APS) which is Rad-hard, has inbuilt ADC and can give direct digital output. It consumes less power compared to the CCD sensor.

2) Electronics design:

Refer block diagram of camera [fig.5.]. The optics in front of the detector focuses the light on to it. FPGA provides the necessary drive signals to drive the APS. The FPGA contains the logic required for auto intensity control. This auto intensity control algorithm will change the exposure time of the camera to get an image irrespective of incident light intensity. The FPGA reads the pixel data of the APS digitized using the on-chip ADC. This is the image representation of the scene in digital form, pixel by pixel, line by line, frame by frame. The image is formatted and sent to onboard data handling system where it is compressed and transmitted to ground. There is provision for gain control and integration time control by commanding from ground.

3) .Choice of System clock.

The input clock to the Navcam is 24 MHz which gives image transfer rate of 3 frames per second. All other clocks are derived from this. The maximum data rate of APS is 12MHz. A de-rated value of 3 frames per second is chosen considering error free transmission to image compression unit..

4) FPGA design:

Fig.5. gives the functional blocks inside the FPGA.
They are
a. APS drive
b. Image formatting for output
c. Command processing block.
The FPGA chosen is Actel RT54 SX 32S which is Radiation tolerant and has 32k gates inside.[4]

a) APS driving:

APS drive signals are generated by means of a finite state machine and sequential blocks. The drive uses 3 MHz clock and state machine is operated on 12Mhz. The address bus is multiplexed between line address read, line address reset, and pixel address as required by detector.

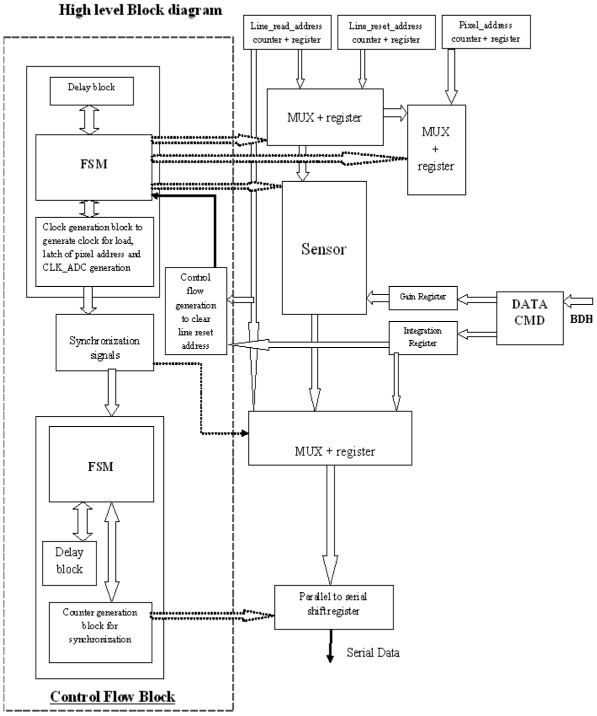

High level Block diagram
Line_read_address counter + register
Line_reset_address counter + register
Pixel_address counter + register
Delay block
FSM
MUX + register
MUX + register
Sensor
Clock generation block to generate clock for load, latch of pixel address and CLK_ADC generation
Control flow generation to clear line reset address
Gain Register
Integration Register
DATA CMD
BDH
Synchronization signals
MUX + register
FSM
Delay block
Counter generation block for synchronization
Parallel to serial shiftregister
Serial Data
Control Flow Block

Figure 6. Architecture of APS drive

I.) CONTROLLER DESIGN:

APS controller design is done by using two finite state machines in a handshaking mode. One SM(State Machine) is used to generate signals required for APS fixed pattern noise removal, calibration of output amplifier signal, generation of required delay for the driving signal, selection between reading and resetting the line address, generation of reset signals, etc (fig.6.). The second SM is for generation of control signals for pixel read, synchronization signals to indicate end of line, end of frame, data_ready and to clear the reset address registers. There are sequential blocks to enable the loading and latching of pixel address in the address bus of the detector and enabling the clock required for A/D conversion. These blocks also select the correct sequence of loading the new integration time. The whole sequence of operations is explained in Fig.7.

II.) DATAPATH DESIGN:

In data path design the address bus is multiplexed between line read address, line reset address, pixel address. This address is fed back to the incrementer block which is enabled by Address controller block. Depending on the Address controller block signal line read address and line reset address will be reset.

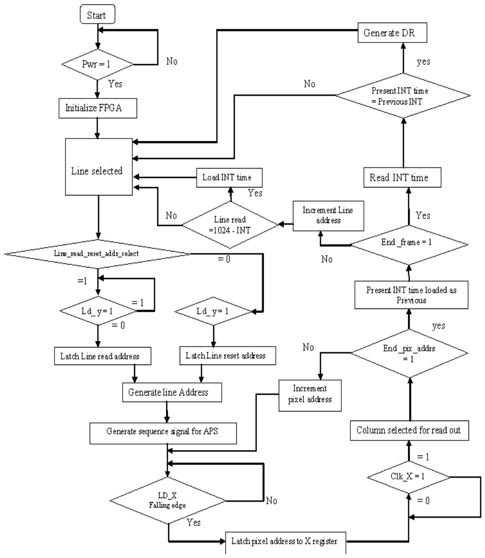


Figure 7 APS drive Flow chart

b) Image formatting for output

The image data from camera is transmitted serially to on board data handling system for storage, compression and transmission to ground.

Serial Interface:

Custom Serial Digital Interface has been chosen for Nav camera to transfer images to data handling subsystem. The signal DATA_ READY, indicates the start of frame. The lines are connected using LVDS transceivers (low voltage differential signaling) through twisted shielded pair. This is to remove common mode noise and transmit large distance without any loss of data.

c) Command processing block

The functionality of the command processing block is to receive the 16 bit command coming serially from BDH and update the command register. This command will be used to control the integration time and gain. This register is scanned by the blocks at the end of each frame to check for the new integration time and gain. Depending on that integration time and gain will be updated in the subsequent frame.

III. DEVELOPMENT TOOLS

- Libero IDE 8.5 : VHDL Editor.
- Core generator : SmartGen
- Synplify 9.1 to synthesize the code
- WaveformerLite to generate test bench graphically
- ModelSim 6.4 A for simulation
- Designer tools to compile, layout making, back annotation
- Silicon Sculpture (to programme the Antifuse FPGA)

IV. INTEGRATION TIME CONTROL

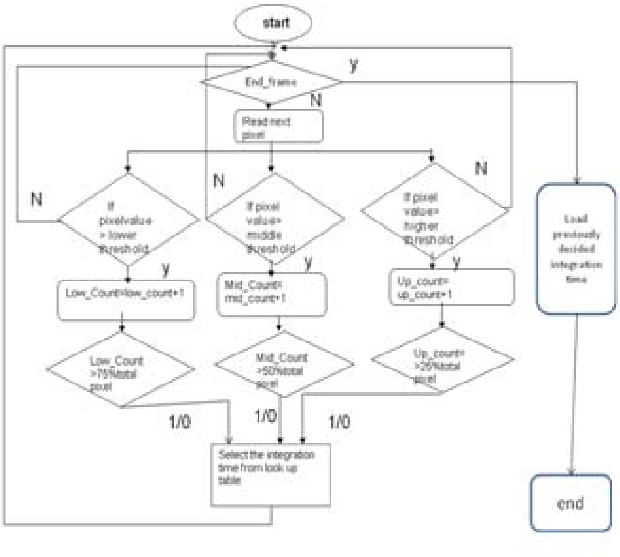
Integration time or camera exposure control is required to avoid

a .*Blooming effect*
b. *Over exposed* image
c. *Under exposed image.*

The integration time is the time between last reset and read out time. During this interval incident light on the photodiode generates electron hole pair (e-h pair). This e-h pair increases the current in photodiode and the accumulated charge on the photo diode will be discharged. Based on the light intensity, the integration time has to be controlled to charge the photodiode. The integration time is the line number having range of 1:1024 lines. When line ‘n’ is read ‘n+T’th line is reset, where ‘T’ lines is the integration time. Thus camera exposure can be controlled by proper adjustment of integration time. The camera receives the telecommand for integration time and FPGA controls the integration time by adjusting the read and reset lines. The exposure should be adjusted in such a way that intensity of different image taken at different lighting condition is same in terms of their intensity level. The latency for integration time to take effect is one frame.

Auto integration time control:

An algorithm to automatically control the exposure time is explained in the flowchart. [Fig.8]. First frame, the image is captured and based on the intensity level, the algorithm will calculate the actual integration time and control the exposure level for the next frame. This algorithm does not require any memory as it calculates the exposure level on the run time. It needs only a 2-bit comparator and 20-bit adder to implement this design.



start
y
End_frame
N
Read next pixel
N
N
N
If pixelvalue > lower threshold
If pixel value> middle threshold
If pixel value> higher threshold
y
y
y
Low_Count=low_count+1
Mid_Count= mid_count+1
Up_count= up_count+1
Load previously decided integration time
Low_Count >75%total pixel
Mid_Count >50%total pixel
Up_count> >25%total pixel
1/0
1/0
1/0
Select the integration time from look up table
end

Figure 8. Flow chart explaining algorithm for auto intensity control

V. GAIN SELECTION:

Through Tele-command it is possible to control the gain of the programmable gain amplifier inside the APS so that better image clarity and contrast are obtained. Gain of the detector is controlled by two bits which are set by FPGA.

VI. THERMAL CONTROL:

As the Rover sees extreme temperatures in moon and since the Navcam is mounted on top of Rover, proper thermal control is needed. Use of heaters, Thermo Electric Cooler or radio isotope on the metallic housing to generate heat are options considered to maintain the operating temperature limits of the Navcam.

VII. PIXEL VOLTAGE CALCULATION.

A. Calculation of the saturation voltage of the Star1000 detector on lunar Surface.

Number of photons for 1 Solar constant (1370W / m^2) =
Photon flux (F) =3.835×10^{21} photons/ m^2 sec.(for 1SC)
Focal length of the optics (FL) = 25mm.
F no = 2
Aperture diameter=FL/f no=12.5 mm.
Object Distance = 10 m.
Magnification (m) = FL/Object Distance = 2.5×10^{-3}.
Area of the aperture (A_{ap}) = Πr^2= $122.72 \times 10^{-6} m^2$
Pixel size= 15µmx15µm.
FOV of the optics full cone = 45°.
Conversion gain of the detector (c.g) = 11 µV/e-.
Minimum integration time of the detector (T_i) = 0.4 ms.
Frame rate = 3 FPS.
Quantum efficiency (QE) = 0.22.
Lunar Surface reflectivity (SR) = 10%.
Transmittance of the lens (T_r) = 90%)
V_{SAT} = 1.1V.
Solid angle subtended at the detector for the given area of the Aperture and focal length is =Area of the Aperture/ (image distance)^2. = A_{ap} / $(FL)^2$ =0.1963 Sr.
Irradiance of the Source=E_{object} =1370 W/m^2
Radiance of the Object = L_{object} = (E_{object} X SR) / Π (1)
= 137/Π W/ (m^2 Sr).
Irradiance on the Detector
= T_r X L_{object} X Solid angle / $[(2 \times Fno) \times (m+1)]^2$
= 0.478 W/m^2 (2)
Number of photons for Irradiance on the Detector (FD) = 0.00134×10^{21} photons/ m^2 sec.
V_{out} = Number of photons for Irradiance on the Detector (FD) x Area of pixel x QE x integration time (T_i) x Conversion_gain. (3)
= 292.36 mV.
For the minimum integration time (1 line) of 0.4ms
Vout = 292.36 mV.
Maximum integration time = (1100/288) x 0.4ms.
= 1.5 ms. (4 line)
For the sun intensity of 1 SC and 10 % of lunar soil reflectivity, the integration time up to 3 lines will not saturate the pixel.

B. Noise Calculations of STAR 1000 Detector.

From ref [7] the noise of the detector is estimated below.

N_{Dark} = Average dark signal (e/s) X Integration time (s) = 0.468 e.
N_{DSNU} = Dark signal Non uniformity (e/s) X Integration time (s) = 0.3 e.
N_{FPN} = Fixed Pattern Noise = 125 e.
N_{kTC} = Temporal Noise = 60e.
Considering the effects of all noise sources the noise model can be expressed as

$$\text{Noise (e)} = \text{Sqrt}\left[(N_{Dark})^2 + (N_{DSNU})^2 + (N_{FPN})^2 + (N_{kTC})^2 \right]. = 138.65 \text{ e} \quad (4)$$

Conversion gain of the detector (c.g) = 11 µV/e-
Noise (mV) = Noise (e) x Conversion gain of the detector. = 1.5 mV
Noise for 0.4ms (1 line) Integration (mV) = 1.5 mV.

D. Calculation of the Integration Time For the worst case light conditions on the Lunar surface.

Minimum Sun intensity in AM0 (assumed) = 10 W/m^2.
V_{SAT} = 1.0V.
Required integration time for minimum sun intensity =190.5 ms.
Number of Integration (Delay) lines = 476.
Noise for 190ms integration time = 3.28mV.
S/N (db) = 49 db.

For the Optics the max and min integration time can be 0.4 ms to 190 ms for the varying light intensities from 1370 W/m^2 to 10 W/m^2

Table III. *Signal to Noise ratio calculation for different Integration Time.*

Sl no	Integration Time	Signal (mV)	Noise (mV)	S/N in db
1	1 line	292	1.52	46
2	2 line	584	1.52	52
3	3 line	876	1.52	55
4	4 line	1168	1.52	58

From the above result, we can conclude that with the increase of integration time signal level increases linearly upto saturation but noise level is not changing as most of the noise contributing is FPN which is fixed and known. Therefore with increase of integration time, it is possible to get higher S/N indicating satisfactory performance even in low light conditions.

VIII. TESTING OF NAVCAM

The testing of Navigation camera involves quantitative estimation of all the parameters like dynamic range, contrast, S/N ratio, range, resolution, etc. The target to be imaged is kept at different distance from the Navcam and calibrated under different light conditions. Standard test charts are imaged and then using slant edge method the MTF [6] can be obtained. MTF will give the actual resolving power of the camera in terms of line pair per mm. The Test System consists of a hardware simulator to give power, commands & clock to the Navcams. A PC with high speed Digital I/O card [PCI 7300 from ADLINK] operating at 3 MHz acquires the image data from both the Navcams. The stereo images from both Navcams are stored in PC memory. The bitmap image is displayed on the monitor. Using stereo ranging and DEM software, the image is analyzed. The Navcams will undergo thermo-vacuum, vibration and shock tests as part of qualification.

IX. DEM GENERATION:

Two Nav cameras will send two overlapping images to the ground as left camera image and right camera image. Standard image filtering and radiometric corrections will be done to enhance the images. From these two images the disparity information for every pixel can be obtained. Depending on the camera orientation, the pixels from two images are matched using image feature extraction and comparing statistical parameters of those pixels. The disparity information thus obtained is used to generate Digital Elevation Model (DEM) for the images [5]. This model will give depth information of the object / obstacle. Accordingly, the path planning from ground is carried out. A DEM also known as a digital terrain model (DTM) is a digital representation of ground surface topography. A DEM can be represented as a raster (a grid of squares) or as a triangular irregular network.

X. FUTURE SCOPE

There are four improvements planned for the camera.

1. By using Cypress IBYS or similar color APS device, this can be made as a color camera.
2. By replacing the FPGA with Rad hard RTAX 4000 with 4 million gates, and using a JPEG/ MPEG encoder IP core inside the FPGA, image compression can be embedded inside the Navcam with marginal increase in weight/ volume / power thereby converting the camera as a system –on –chip.
3. Camera interface can be made as Spacewire, Camera link or CCIR656, by incorporating the protocol or engine inside the FPGA. The data rate can be increased.
4. Further miniaturization of Navcam is possible by reducing the optics format from 1 inch to ½ inch. By suitably modifying the DEM software, the image characteristics can be improved.

XI. CONCLUSION

The design of a state-of-the art, miniature navigation camera for Lunar mission is presented in this paper. The design constraints for operation in lunar environment and weight, volume, power, etc which are premium are the challenges involved. The proto model of the camera is developed, tested and integrated with the Rover. The future improvements planned for the camera are also addressed. Similar Navigation cameras were flown in planetary missions to Mars, moon, etc. The quantitative results for camera will be generated after subjecting the images to DEM generation software.

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